

Testing the Isotropy of Signal Propagation Using Distributed Precision Timing

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April 2026

Abstract

The isotropy of the speed of light is a foundational assumption in modern physics, strongly supported by numerous experimental tests. However, many of these tests primarily constrain the constancy of the two-way (round-trip) speed of light and have been conducted within relatively limited spatial, velocity, and environmental regimes. This work proposes a distributed timing experiment using spacecraft and high-precision clocks to probe potential anisotropies in signal propagation across extended baselines and varying conditions. By analyzing residual timing deviations relative to standard relativistic predictions, the experiment aims to determine whether isotropy holds universally or represents an approximation valid within currently tested regimes. Any detected anisotropy could influence the interpretation of long-distance signal measurements and inform our understanding of the underlying structure of spacetime.

1 Introduction and Motivation

The isotropy of the speed of light is a central assumption in modern physics, particularly in special relativity, and is strongly supported by a wide range of experimental tests. This assumption underlies both theoretical formulations and practical systems such as the Global Positioning System (GPS) [3].

Many experimental confirmations of relativity, however, primarily constrain the constancy of the *two-way* (*round-trip*) speed of light. Direct empirical determination of one-way propagation properties over large distances remains fundamentally dependent on synchronization conventions, limiting the range of conditions under which directional propagation symmetry has been independently tested.

As a result, existing tests of isotropy have been conducted primarily within:

- local or near-Earth environments
- relatively limited spatial baselines compared to interstellar or intergalactic scales
- modest relative velocity regimes between experimental platforms

These constraints leave open the possibility that directional or environment-dependent propagation effects, if present, may not be detectable within currently explored regimes.

This work proposes an experimental framework designed to extend empirical testing of signal propagation into regimes involving larger spatial scales, broader environmental variation, and greater relative motion, with the goal of determining whether isotropy holds under these expanded conditions.

2 Hypothesis

Signal propagation may exhibit a physical (Type A) anisotropy relative to an underlying structure or preferred frame, with propagation characteristics depending on direction, velocity, or environment.

No assumption is made regarding the magnitude or functional form of this effect.

3 Null Hypothesis

Signal propagation is isotropic and fully consistent with predictions from special and general relativity within experimental precision.

4 Toy Model of Anisotropy

As an illustrative model, consider a direction-dependent propagation speed:

$$c(\theta) = c_0 (1 + \alpha \cos \theta)$$

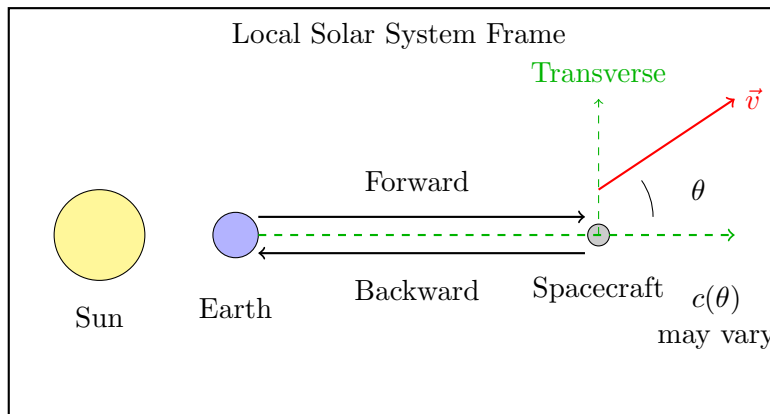
where:

- c_0 is the standard (isotropic) speed of light
- α is a dimensionless parameter characterizing the magnitude of anisotropy
- θ is the angle between the signal propagation direction and the velocity of the local frame relative to a possible preferred frame

In this model, $\alpha = 0$ corresponds to isotropic propagation. Nonzero values of α introduce directional dependence in the propagation speed.

This model is not assumed to describe physical reality, but serves as a simple framework for illustrating how directional anisotropy could manifest in measured timing data.

5 Conceptual Diagram



The vector $\vec{v}$ represents the velocity of the local frame (Earth/spacecraft system) relative to a possible preferred frame. The angle θ defines the direction of signal propagation relative to this motion.

The spacecraft follows its own inertial trajectory within the local frame; however, the anisotropy under consideration depends on the motion of the local frame relative to the underlying structure, rather than on the spacecraft's motion alone.

6 Experimental Framework

A distributed timing system is established between Earth and spacecraft equipped with ultra-precise clocks.

Continuous bidirectional communication records:

- Earth transmission times
- spacecraft reception times (local clock)
- spacecraft transmission times
- Earth reception times

7 Measurement Methodology

Residual timing differences are computed as:

$$\Delta t = t_{\text{observed}} - t_{\text{predicted}}$$

where $t_{\text{predicted}}$ is calculated under isotropic assumptions.

The objective is to identify systematic residuals that cannot be accounted for by known relativistic effects or by allowable synchronization conventions.

8 Implications for Signal Interpretation

If physical anisotropy exists, it may affect interpretation of signals over large distances.

- **Doppler Measurements:** Direction-dependent propagation could alter the relationship between observed frequency shifts and inferred velocities, potentially affecting astrophysical redshift interpretation.
- **Long-Distance Timing:** Propagation delays may become direction- or path-dependent over large baselines.
- **Synchronization:** High-precision synchronization across large distances may exhibit inconsistencies under isotropic assumptions.

9 Related Work and Prior Experiments

Numerous experiments have tested aspects of light propagation and relativity, including:

- Michelson–Morley-type experiments [1]
- Modern optical cavity experiments [2]
- Satellite-based timing systems such as GPS [3]
- Deep-space tracking experiments [4]
- Tests within the Standard-Model Extension (SME) framework [5]

These experiments strongly constrain deviations from isotropy within currently accessible regimes. However, they primarily probe local or near-Earth conditions, limited spatial scales, and relatively modest velocity differences between experimental platforms.

As a result, it remains possible that direction- or velocity-dependent propagation effects, if present, could remain below current detection thresholds in these regimes while becoming observable under extended baselines or higher relative velocities.

10 Expected Outcomes

10.1 Null Result

$\Delta t \approx 0$, consistent with isotropic propagation within tested regimes.

10.2 Non-Null Result

Systematic residuals indicating directional, velocity-dependent, or environmental variation in propagation behavior.

11 Conclusion

This work proposes a direct empirical test of a foundational assumption in modern physics: the isotropy of signal propagation. By extending measurement regimes in spatial scale, environmental variation, and relative motion, the proposed experiment aims to determine whether isotropy remains consistent under broader conditions than those currently tested.

The proposed experiment complements existing tests by directly probing regimes that have not been extensively explored in combination.

A null result would further strengthen confidence in existing theoretical frameworks across an expanded domain. A non-null result, if observed, would warrant careful investigation and could suggest that current models represent highly accurate approximations within certain regimes, analogous to the relationship between Newtonian mechanics and relativity.

In either case, the outcome contributes to refining our empirical understanding of signal propagation and its role in physical theory.

References

References

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